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# Transmission Scheduling in Capture-Based Wireless Networks

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**Abstract** We study a multiple-source, single-destination wireless network that uses scheduled access as the channel-access method. Unlike many other studies of scheduled access, which are based on the use of a collision channel, we use a physical channel model that includes other-user interference, fading, and background noise. Our primary performance measure is throughput, which is the average number of packets that are successfully received by the destination per time slot. We develop algorithms for constructing transmission schedules, which exploit the power-capture capability of the network to enable the successful reception of multiple packets simultaneously. The results show the impact of schedule, channel fading, receiver noise, and interference on network performance. Our algorithms provide better performance than TDMA-based algorithms that do not take advantage of the power-capture capability of the network.

## 1 INTRODUCTION

In this paper, we study a wireless network in which $K$ source nodes transmit data to a common destination. The network operates in the presence of detrimental effects such as channel fading and receiver noise. An application for our model is a wireless sensor network, which consists of $K$ sensor nodes transmitting data to a collection center. Fig. 1 shows such a network in which $K = 6$ sources transmit to a destination ($D$).

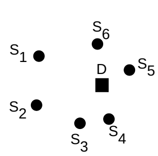


Fig. 1 A wireless network with 6 sources ($S_i$) and a destination ($D$)

We assume that all the nodes in the network share a common channel, and we are interested in medium-access-control (MAC) methods for a heavy-traffic model, in which each source node always has traffic to transmit. Thus, contention-based protocols such as CSMA [3], which work well under bursty traffic, would not be appropriate for our steady traffic requirement.

Our performance measure is throughput, which is the average number of packets that are successfully received by the destination per time slot. A major issue due to the sharing a common channel is other-user interference that results when several nodes transmit in the same time slot. Scheduled-based protocols such as the well-known TDMA approach can be used to eliminate/reduce other-user interference, i.e., each source node is given a turn to transmit. Thus, there is exactly one transmission in each time slot.

In this paper, we consider a power-capture-based approach, under which more than one transmission is allowed in a time slot. That is, a packet is successfully received, even in the presence of interference and noise, as long as its signal-to-interference-plus-noise ratio (SINR) exceeds a given threshold [4, 5, 11]. The capture-based approach can significantly outperform the TDMA approach.

Our goal is to develop algorithms for constructing transmission schedules. Each schedule specifies which group of nodes are allowed to transmit in each particular time slot. Our proposed algorithms, which have polynomial-time complexity, exploit the multiple-packet-reception capability of the network, and address the impact of other-user interference. We study the issue of transmission scheduling in a capture-based wireless network under heavy, steady-traffic load. Thus, it is not meaningful to compare our results to other practical protocols such as CSMA [3], CDMA [8], or 802.11, which are based on different assumptions about available resources and capabilities.

The paper is organized as follows. In Section 2, we specify the model and the assumptions for the multiple-source single-destination network used in the paper. We use a physical channel model that incorporates other-user interference, fading, and background noise. In Section 3, we present analytical methods for throughput evaluation, which incorporate the transmission schedules, network topology, and channel statistics. In Section 4, we present algorithms for constructing transmission schedules to be used by the nodes in the network. We then show the performance comparison among those algorithms. We summarize our contribution in Section 5.

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## 2 NETWORK MODEL AND ASSUMPTIONS

We consider a stationary wireless network that has $K$ source nodes, denoted by $S_1, S_2, \dots, S_K$, that transmit their traffic to a common destination, denoted by $D$. An example network with $K = 6$ sources is shown in Fig. 1. We assume the following:

- The nodes, whose locations are known and fixed, are equipped with omnidirectional antennas.
- The destination can receive more than one successful transmission at a time, i.e., it has multiple reception capability.
- Each source node can communicate directly with the destination. Routing is not discussed in this paper. However, our model can be extended to include multi-hop communication by allowing some nodes to receive and then to transmit/forward to downstream nodes.
- Each source node always has traffic to transmit, i.e., its transmission queue is never empty.
- Time is divided into slots. The traffic is expressed in terms of fixed-size packets such that it takes one time slot to transmit one packet. A frame consists of $M_{\text{frame}}$ consecutive time slots.
- Our primary performance measure is throughput, which is the average number of packets that are successfully received by the destination per time slot. We do not address issues such as time delays and stability analysis in this paper.
- Nodes transmit according to a schedule, i.e., a node can transmit only in an assigned time slot.
- Each source node transmits exactly once in each frame, and that the schedule repeats from frame to frame. Thus, it is sufficient to study the performance in any one frame.

**Definition 1** A *schedule* is a tuple

$$(H_1, H_2, \dots, H_{M_{\text{frame}}})$$

where $H_k$ is the set of source nodes that simultaneously transmit in time slot $k$. □

Later in the paper, we present several algorithms for constructing schedules, in which the frame length $M_{\text{frame}}$ and the sets $H_k$ are determined, $k = 1, 2, \dots, M_{\text{frame}}$.

The network operates according to the principle of power capture, i.e., a packet is successfully received, even in the presence of interference and noise, as long as its signal-to-interference-plus-noise ratio (SINR) exceeds a given threshold [4, 5, 11]. More precisely, suppose that we are given a set $H$ of source nodes that transmit in the same time slot. For each $S \in H$, let $P_{\text{rx}}(S, D)$ be the signal power received from node $S$ at node $D$, and let $\text{SINR}(S, D)$ be the SINR determined by node $D$ due to the transmission from node $S$, i.e.,

$$\text{SINR}(S, D) = \frac{P_{\text{rx}}(S, D)}{P_{\text{noise}} + \sum_{U \in H \setminus \{S\}} P_{\text{rx}}(U, D)}$$

where $P_{\text{noise}}$ denotes the receiver noise power at node $D$. We assume that a packet transmitted by $S$ is successfully received by $D$ when

$$\text{SINR}(S, D) > \beta \qquad (1)$$

where $\beta \geq 0$ is a threshold at node $D$, which is determined by application requirements and the properties of the network. When $\beta < 1$ (e.g., in spread-spectrum networks), it is possible for two or more transmissions to satisfy (1) simultaneously [6].

The wireless channel is subject to fading, as described below. Let $P_{\text{tx}}(S)$ be the transmit power at node $S$, and $r(S, D)$ be the distance between nodes $S$ and $D$. When node $S$ transmits, the power received by node $D$ is modeled by

$$P_{\text{rx}}(S, D) = A(S, D) g(S, D)$$

where $A(S, D)$ is a random variable that incorporates the channel fading. We refer to $g(S, D)$ as the "received power factor," which depends on $r(S, D)$ and $P_{\text{tx}}(S)$. For far-field communication (i.e., when $r(S, D) \gg 1$), we have

$$g(S, D) = P_{\text{tx}}(S) r(S, D)^{-a} \qquad (2)$$

where $a$ is the path-loss exponent (typical values of $a$ are between 2 and 4). A simple approximate model for both near-field (i.e., when $r(S, D) < 1$) and far-field communication is

$$g(S, D) = P_{\text{tx}}(S)[r(S, D) + 1]^{-a} \qquad (3)$$

where the term $r(S, D) + 1$ is used to ensure that $g(S, D) \leq P_{\text{tx}}(S)$. Under Rayleigh fading, $A(S, D)$ is exponentially distributed [9, p. 36].

Our goal is to study methods for accomplishing the communication between the sources and destinations, and to analytically evaluate the resulting performance. Under the well-known traditional TDMA method, each source node is given a turn to transmit, i.e., there is exactly one transmission and no other-user interference in each time slot. In this paper, we consider power-capture-based approaches, as described in the following sections, under which more than one transmission is allowed in a time slot.

## 3 THROUGHPUT EVALUATION

Suppose that the network operates according to schedule $(H_1, H_2, \dots, H_{M_{\text{frame}}})$, where $H_k$ is the set of source nodes that simultaneously transmit in time slot $k$. Let $C^k_{H_k}(S, D)$ be the probability that a packet from source node $S$ is successfully received by destination $D$, and $C_{\text{success}}(k)$ be the average total number of successful transmissions in time slot $k$. We then have

$$C_{\text{success}}(k) = \sum_{S \in H_k} C^k_{H_k}(S, D) \qquad (4)$$

We now define *throughput* $T$ to be the average number of packets that are successfully received by the destination per time slot. Recall that there are $M_{\text{frame}}$ time slots in a frame. The throughput is then

$$T = \frac{1}{M_{\text{frame}}} \sum_{k=1}^{M_{\text{frame}}} C_{\text{success}}(k)$$

which, from (4), becomes

$$T = \frac{1}{M_{\text{frame}}} \sum_{k=1}^{M_{\text{frame}}} \sum_{S \in H_k} C_{H_k}^k(S, D) \tag{5}$$

For the case of Rayleigh fading, the following result provides the exact formula for $C_{H_k}^k(S, D)$, which depends on the receiver noise, channel fading, receiver threshold, and other-user interference.

**Theorem 1** Suppose that the fading between a transmitting node $S$ and a receiving node $D$ is modeled as a Rayleigh random variable $Y_S$ with parameter $v(S, D)$. For $S \neq U$, assume that $Y_S$ and $Y_U$ are independent. Let $g(S, D)$ denote the received power factor, which depends on the distance and the transmit power, e.g., $g(S, D) = P_{\text{tx}}(S) r(S, D)^{-a}$ or $g(S, D) = P_{\text{tx}}(S) \left[r(S, D) + 1\right]^{-a}$. Given that all the nodes in $H_k$ simultaneously transmit in time slot $k$, the probability that a packet from $S$ is successfully received by $D$ is given by

$$\begin{aligned} C_{H_k}^k(S, D) &= \frac{\exp\left(-\frac{\beta P_{\text{noise}}}{v(S,D)g(S,D)}\right)}{\prod_{U \in H_k \setminus \{S\}} \left[1 + \beta \frac{v(U,D)g(U,D)}{v(S,D)g(S,D)}\right]} \\ &= \frac{(1+\beta)\exp\left(-\frac{\beta P_{\text{noise}}}{v(S,D)g(S,D)}\right)}{\prod_{U \in H_k} \left[1 + \beta \frac{v(U,D)g(U,D)}{v(S,D)g(S,D)}\right]} \end{aligned}$$

where $\beta$ and $P_{\text{noise}}$ are the required SINR threshold and the receiver noise power at $D$, respectively.

**Proof** See [2, 7].

**Remark 1** The throughput $T$ in (5) has the form of *summation*. Other forms of throughput are also possible, e.g., the following product-form measure of throughput

$$T_{\text{prod}} = \left( \prod_{k=1}^{M_{\text{frame}}} \prod_{S \in H_k} C_{H_k}^k(S, D) \right)^{\frac{1}{M_{\text{frame}}}}$$

may be appropriate for a model that encourages fairness among the nodes in the network (recall that each node transmits exactly once in each frame). However, this paper presents performance results only for the sum throughput given by (5).

**Remark 2** For a given schedule, we can analytically compute the throughput $T$ in (5). The computation of $T$ requires a double sum that adds $K$ terms of the form $C_{H_k}^k(S, D)$. The computation of $C_{H_k}^k(S, D)$ in turn requires a product of $\mathrm{O}(|H_k|)$ terms (by Theorem 1). Because $|H_k| \leq K$, the overall computational complexity for computing $T$ is then bounded by $\mathrm{O}(K^2)$.

**Remark 3** Let $H$ be the set of nodes that simultaneously transmit in a time slot over the Rayleigh-fading channel. Suppose we allow an additional node $S' \notin H$ to transmit in the same time slot, i.e., the new set of transmitting nodes in the time slot becomes $H' = H \cup \{S'\}$.

For each $S \in H$, using Theorem 1, it can be shown that

$$C_{H'}(S, D) = C_H(S, D) \left[1 + \beta \frac{v(S', D)g(S', D)}{v(S, D)g(S, D)}\right]^{-1}$$

i.e., with the additional transmission from the new node $S'$, the probability of successful transmission from an original node $S$ is reduced by the factor $1 + \beta v(S', D)g(S', D)/[v(S, D)g(S, D)]$. Using Theorem 1, we have

$$C_{H'}(S', D) = \frac{(1+\beta)\exp\left(-\frac{\beta P_{\text{noise}}}{v(S',D)g(S',D)}\right)}{\prod_{U \in H'} \left[1 + \beta \frac{v(U,D)g(U,D)}{v(S',D)g(S',D)}\right]}$$

Thus, when the value of $C_H(S, D), S \in H$, is known, the value of $C_{H'}(S, D)$ is computed with complexity $\mathrm{O}(1)$. However, the computation of $C_{H'}(S', D)$ requires complexity $\mathrm{O}(H')$.

**Remark 4** The throughput $T$, which is the average number of packets that are successfully received by the destination per time slot, is given in (5) for an arbitrary schedule. We now consider two special cases. The first special case is the TDMA schedule for which there is exactly one transmission in each time slot (i.e., there is no other-user interference). Under TDMA, we have $M_{\text{frame}} = K$ and $|H_k| = 1$. From (5), the throughput for the TDMA method is

$$T_{\text{TDMA}} = \frac{1}{K} \sum_{i=1}^{K} C_{\{S_i\}}^i(S_i, D)$$

We must have $T_{\text{TDMA}} \leq 1$. This upper bound is achieved under the ideal condition $P_{\text{noise}} = 0$. The second special case is the schedule of frame length $M_{\text{frame}} = 1$, under which *all* nodes transmit in each slot. We then have $H_1 = \{S_1, \ldots, S_K\}$. From (5), the throughput for this all-at-once method is

$$T_{\text{ALL}} = \sum_{i=1}^{K} C_{(H_1)}^1(S_i, D)$$

## 4 ALGORITHMS FOR SCHEDULE CONSTRUCTION

Recall that we define a schedule in terms of a frame (Definition 1). Each frame has $M_{\text{frame}}$ time slots. The set of source nodes that transmit in time slot $k$ is denoted by $H_k$. Similar to the TDMA method, our capture-based method also requires that each source node transmits *once* in each frame. However, our method allows the possibility of more than one transmission in a time slot, i.e., we may have $|H_k| > 1$ for some $k$. Under the TDMA method, we have

$M_{\text{frame}} = K$ and $|H_k| = 1$ for all $k$. Under the capture-based method, we have $1 \le M_{\text{frame}} \le K$ and $|H_k| \ge 1$ for all $k$.

Let us consider an arbitrary schedule $(H_1, H_2, \ldots, H_{M_{\text{frame}}})$. Because we require that *each* source node transmits *once* in each frame, we must have $\{S_1, S_2, \ldots, S_K\} = \cup_{i=1}^{M_{\text{frame}}} H_i$ and $H_i \cap H_j = \emptyset$ for $i \ne j$. Thus, the schedule is associated with a partition of the set of the $K$ source nodes. The number of possible schedules is then the number of different partitions of the set of the $K$ source nodes. This number, called the Bell number $B_K$ [p. 65, 1], obeys the recursion

$$B_{n+1} = \sum_{k=0}^{n} \binom{n}{k} B_k \tag{6}$$

with $B_0 = 1$. The Bell numbers grow rapidly, e.g., $B_2 = 2$, $B_3 = 5$, $B_7 = 877$, $B_{10} = 115975$, and $B_{13} = 27644437$.

To summarize, we can compute the throughput $T$ in (5) for each of the $B_K$ schedules. Thus, our model and formulation naturally lead to the following schedule optimization problem: Find an optimal schedule that maximizes the throughput $T$.

### 4.1 Algorithms for Schedule Construction

We now present several centralized algorithms for constructing schedules used by the $K$ source nodes for transmitting their packets to the destination.

**TDMA Algorithm (TDMA)** Under TDMA, there is exactly one transmission in each time slot of the frame. Thus, there is no other-user interference. The frame length is $M_{\text{frame}} = K$. The throughput for the TDMA method is given in Remark 4. The TDMA Algorithm has constant computational complexity, i.e., O(1). A major disadvantage of TDMA is that it does not exploit the capture capability of the receiver (which allows successful reception of multiple packets in a single time slot).

**ALL Algorithm (ALL)** Under ALL, *all* source nodes transmit in each time slot of the frame (i.e., $M_{\text{frame}} = 1$). The ALL Algorithm also has constant computational complexity, i.e., O(1). A major disadvantage of ALL is that it results in maximum other-user interference in each time slot.

**Optimal Algorithm (OPT)** Under OPT, we compute the throughput values for all $B_K$ possible schedules, and then choose an optimal schedule that yields the maximum throughput (i.e., an optimal schedule is found by an exhaustive search). Here, $B_K$ is the Bell number, which is also the number of different partitions of the set of the $K$ source nodes [see (6)]. This number is very large, even for moderate values of $K$, e.g., $B_{30} \approx 8.467 \times 10^{23}$. Although OPT yields the best possible throughput, it has the disadvantage of high computational complexity. For a given schedule, the throughput can be determined with complexity $\mathrm{O}(K^2)$ by Remark 2. Thus, the overall complexity of OPT is $\mathrm{O}(B_K)\times\mathrm{O}(K^2)$.

The above algorithms are straightforward and non-constructive in the sense that we are given a complete schedule, and then the throughput is evaluated for that particular schedule. For example, the complete schedules $(\{S_1\}, \{S_2\}, \ldots, \{S_K\})$ and $(\{S_1, S_2, \ldots, S_K\})$ are chosen in TDMA and ALL algorithms, respectively. In OPT, all $B_K$ possible complete schedules are considered, and the throughput for each complete schedule is computed. In the following, we present heuristic algorithms that are constructive. The main idea is to schedule a source node in the first time slot, based on throughput performance. At the next step, another source node is scheduled, and so on. The process stops after all the source nodes are scheduled.

**Algorithm 1** This algorithm has $K$ steps. At step 1, source node $S_1$ is scheduled for time slot 1. At step $i$, source node $S_i$ is scheduled for time slot $m$ that will result in the maximum throughput. Here, the throughput is computed according to (5), where $M_{\text{frame}}$ is the size of the frame constructed up to the current step. Note that $m$ can be a slot constructed in a previous step (i.e., $S_i$ will share the slot with some other previous source nodes) or $m$ can be a new slot. The algorithm stops at step $K$ when the final source node $S_K$ is scheduled. Algorithm 1 has $K$ steps. At each step, we search for the best slot among the $\mathrm{O}(K)$ slots to schedule a new source node. When a new source node is scheduled in a time slot, the new throughput can be computed with complexity $\mathrm{O}(K)$ (by Remark 3). Thus, the overall complexity for Algorithm 1 is $K \times \mathrm{O}(K) \times \mathrm{O}(K) = \mathrm{O}(K^3)$. In this algorithm, for simplicity, the source nodes are scheduled one by one in the natural order $S_1, S_2, \ldots, S_K$. However, any other form of ordering will also work.

**Algorithm 2** This algorithm also has $K$ steps. At step 1, the source node with the maximum throughput (e.g., the one closest to the destination) is scheduled for time slot 1. At step $i$, we choose a new source node $S_j$ and a time slot $m$ such that, when $S_j$ is scheduled for $m$, the throughput (computed up to this step) is maximized. Note that $m$ can be a slot constructed in a previous step (i.e., $S_j$ will share the slot with some other previous source nodes) or $m$ can be a new slot. The algorithm stops at step $K$ when all the source nodes are scheduled. The algorithm has $K$ steps. At each step, we search for the best source-slot pair among the $\mathrm{O}(K^2)$ such pairs. The best source-slot pair is determined by computing the resulting throughput, which has complexity $\mathrm{O}(K)$ by Remark 3. Thus, the overall complexity for Algorithm 2 is $K \times \mathrm{O}(K^2) \times \mathrm{O}(K) = \mathrm{O}(K^4)$. In this algorithm, the nodes are scheduled in an order that may differ from the natural order $S_1, S_2, \ldots, S_K$.

### 4.2 Performance Evaluation

In this section, we compare the throughput performance, by numerical examples, for the above algorithms. We assume the following:

- The path-loss exponent is $a = 3$.
- The wireless channel is subject to Rayleigh fading with Rayleigh parameter $v(S, D) = 1$.

- The received power factor is given by (3), i.e., $g(S, D) = P_{\text{tx}}(S)[r(S, D) + 1]^{-a}$.
- The transmit power is $P_{\text{tx}}(S) = 1$ for all source nodes $S$. The receiver noise power at the destination is $P_{\text{noise}} = 0.001$

We now study a stationary wireless network, which consists of $K$ source nodes that are located randomly in the circle centered at (0, 0) and of radius $r = 5$, as shown in Fig. 2. The destination is located at $(0, x_D)$. Our performance curves show the throughput $T$ versus the receiver threshold $\beta$. The values of throughput are averaged over 100 random network instances. In the following, we compare the performance of the above algorithms (i.e., TDMA, ALL, OPT, Algorithms 1 and 2) for various network sizes and topology configurations. Note that the throughput values for the TDMA Algorithm ($T_{\text{TDMA}}$) and for the ALL algorithm ($T_{\text{ALL}}$) are computed as in Remark 4.

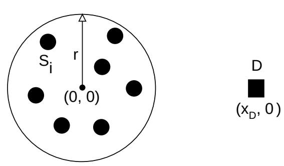


Fig. 2 A wireless network with $K$ sources ($S_i$) and a destination ($D$)

We start by considering a small network with $K = 10$ source nodes. First, we let $x_D = 0$, i.e., the destination is located at the center of the circular region in which the sources are distributed. The performance results are shown in Fig. 3. Smaller $\beta$ typically results in higher throughput $T$. Recall that throughput $T$ is defined to be the number of packets that are successfully received per slot. It is well-known that smaller $\beta$ may result in lower bit rate per transmission, even at higher packet throughput. The translation from packet throughput into bit rate is discussed in [10].

Fig. 3 shows that, as expected, OPT (which is computationally expensive) performs best for all $\beta$, TDMA performs poorly for lower values of $\beta$ and performs well for $\beta \geq 1$, whereas ALL performs well for lower values of $\beta$ and performs poorly for higher values of $\beta$.

We observe that Algorithms 1 and 2 (both of which have polynomial-time complexity) perform almost identically for all values of $\beta$. They perform almost identically to OPT for lower and higher values of $\beta$, namely for $0 \leq \beta < 0.1$ and $\beta \geq 1$. They also outperform both TDMA and ALL algorithms for all $\beta \geq 0$.

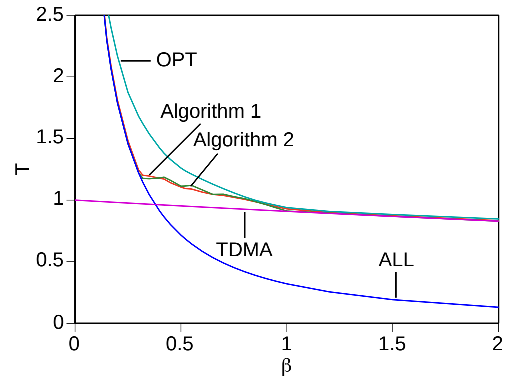


Fig. 3 Throughput ($T$) vs threshold ($\beta$) for $K = 10$ and $x_D = 0$

Next, we let $x_D = 10$. Thus, the destination $D$ is outside the circle of radius $r = 5$. The performance results, which are shown in Fig. 4, are lower than those for the case $x_D = 0$. This is because the distances between the sources and the destination are larger, which imply that the SINR determined at the destination is now reduced.

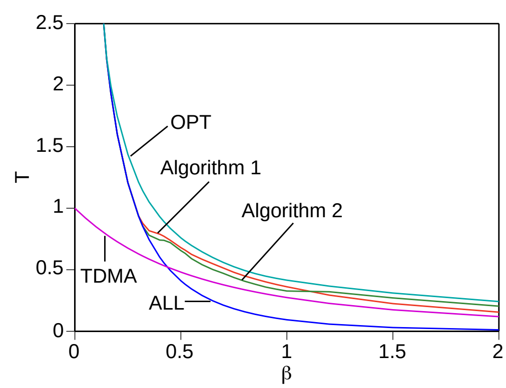


Fig. 4 Throughput ($T$) vs threshold ($\beta$) for $K = 10$ and $x_D = 10$

We now consider a larger network with $K = 100$ nodes. It is not feasible to apply OPT, which has high computational complexity, to the network with this large size. The throughput results are shown in Fig. 5 (for $x_D = 0$) and Fig. 6 (for $x_D = 10$). We observe that Algorithm 2 outperforms Algorithm 1 for a wide range of $\beta$ values. As expected, our two heuristic algorithms outperform both the ALL and TDMA algorithms.

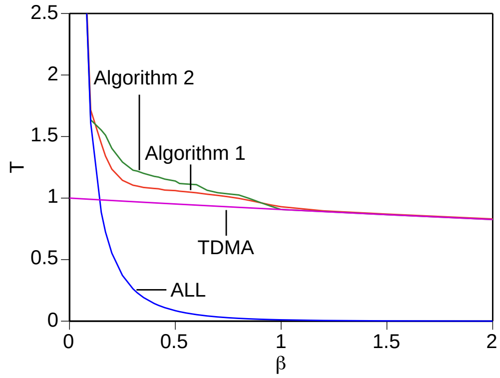


Fig. 5 Throughput ($T$) vs threshold ($\beta$) for $K = 100$ and $x_D = 0$

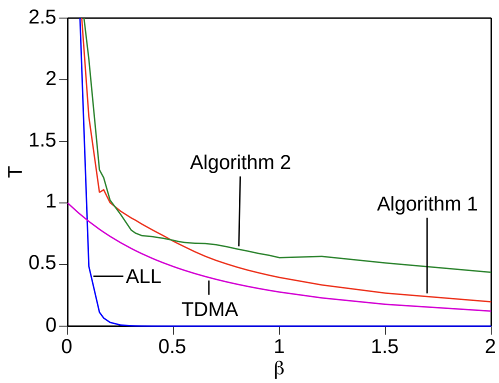


Fig. 6 Throughput ($T$) vs threshold ($\beta$) for $K = 100$ and $x_D = 10$

## 5 SUMMARY

This paper considers a packetized, multiple-source, single-destination wireless network, which operates under the power-capture principle, as well as under realistic conditions such as receiver noise, fading, and other-user interference. Our proposed heuristic algorithms, which have polynomial-time complexity, are simple yet effective methods for constructing schedules for accomplishing the transmissions between the source nodes and the destination. By exploiting the power-capture capability of the network to enable the successful reception of multiple packets simultaneously, our algorithms provide better performance than TDMA-based algorithms that do not take advantage of the power-capture capability of the network.

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